Do hydrocarbon prospects still exist in the East-Carpathian Cretaceous flysch nappes ?

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ABSTRACT

Although Cretaceous strata are involved in most of the East-Carpathian nappes, only the Ceahlau, Bobu, Teleajen, Macla and Audia nappes are composed mainly of Cretaceous flysch. Seeps occurring in the Teleajen nappe and shows obtained from the Macla nappe suggest the existence of a petroleum system which is related to the Cretaceous flysch.

Effective Barremian-Aptian source-rocks are present in Teleajen nappe and Cenomanian-Turonian source-rocks occur in Macla nappe while potential, mostly Albian source-rocks are largely developed in the Bobu and Teleajen nappes.

Reservoir rocks are present in all Cretaceous flysch nappes. However, as these reservoirs generally occur in very high structural positions, they are deeply eroded, except in the Bobu and Teleajen nappes where they can be structurally trapped beneath more internal thrust sheets. Lateral facies changes may provide for the stratigraphic traps in these tectonic units.

We conclude that hydrocarbon prospects still exist in the subthrust parts of the Teleajen and Bobu nappes.

INTRODUCTION

Romania is located in area where the Carpathian Alpine structure draws a large loop and is thrust a considerable distance over the autochthonous foreland. Prior to attaining its present structural configuration (Fig. 1), the on-shore areas of Romania underwent a long and complex geological evolution during which a large number of sedimentary basins developed, both under extensional and compressional conditions. In most of these basins source- and/or reservoir-rocks were deposited. Unfortunately, only part of these sedimentary basins evolved into petroleum systems which today produce hydrocarbons.

Although none of the proven petroleum systems of Romania can be clearly related to Cretaceous source-rocks, a few fields located on the Moesian Platform are thought to be possibly charged by hydrocarbons generated by Cretaceous source-rocks (Paraschiv, 1979). Similarly, oil fields of the East-Carpathians, producing from Tertiary reservoirs (Dicea, this volume), may have been partly charged with hydrocarbons generated by Cretaceous source-rocks (Roure et al., 1993; see

STEFANESCU, M. & BALTES, N., 1996. — Do hydrocarbon prospects still exist in the East-Carpathian Cretaceous flysch nappes ? *In*: ZIEGLER, P. A. & HORVÁTH, F. (eds), Peri-Tethys Memoir 2: Structure and Prospects of Alpine Basins and Forelands. *Mém. Mus. natn. Hist. nat.*, **170**: 427-438 + Enclosure 1. Paris ISBN: 2-85653-507-0.
This article includes 1 enclosure.

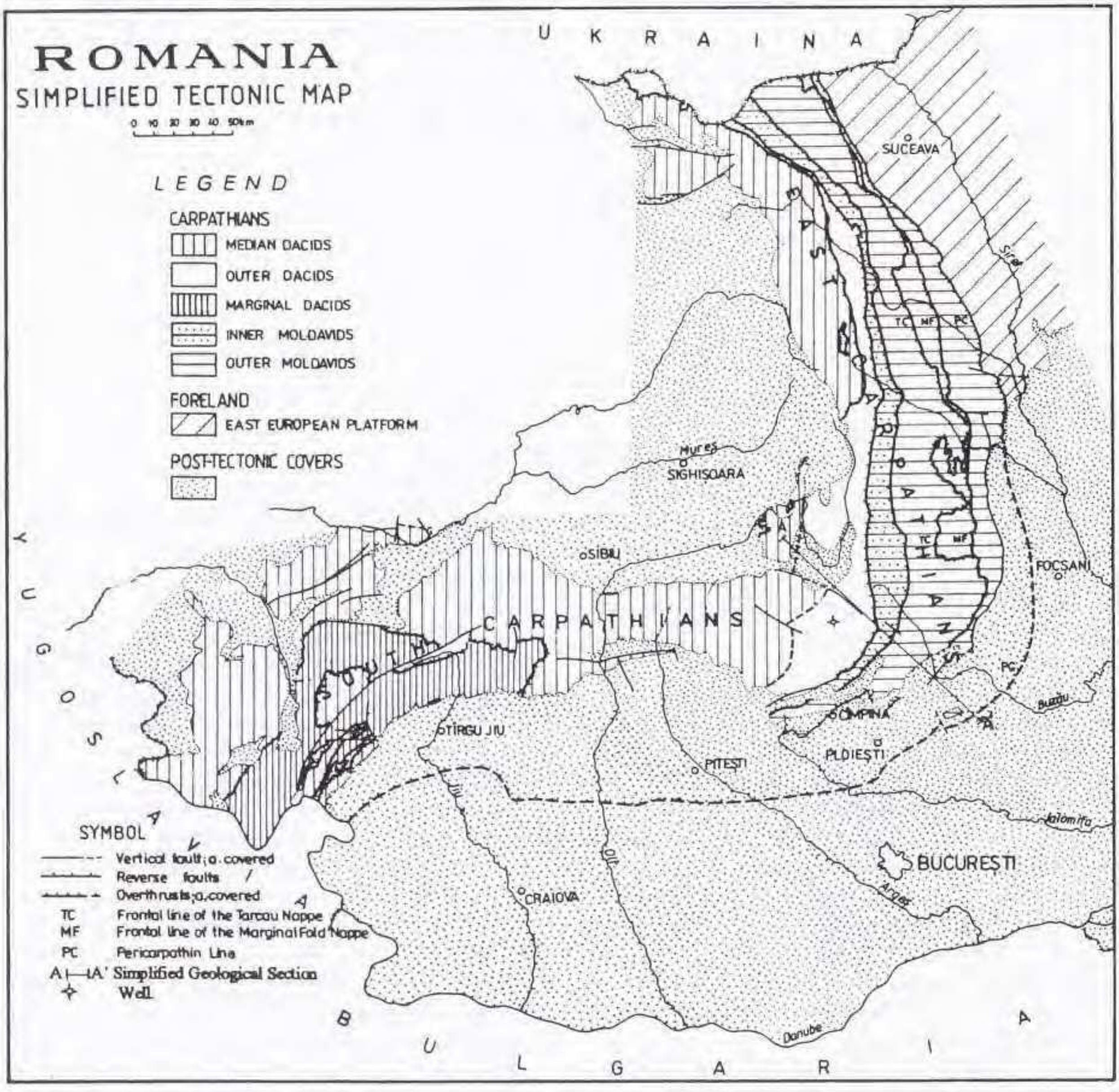

FIG. 1. Romania, simplified tectonic map

also Bessereau et al., this volume). This would not be all that surprising if we take into account that Cretaceous formations are well developed in the Romanian on-shore areas and that, on a world-wide scale, about one third of the total reserves are related to Cretaceous source-rocks and reservoirs (Klemme and Ulmishek, 1991).

On the Moesian Platform, Early Cretaceous carbonates (limestones and dolomites), clastics (clays, marls and sandstones) and evaporites (gypsum) reach total thicknesses of 300 to 1000 m. After an Aptian break, sedimentation of marls and sands resumed during the Albian and persisted till the end of the Senonian, albeit with uneven thicknesses and areal distribution. The Moesian Platform extends deeply under the East-Carpathian fold-and-thrust belt. In the latter, synorogenic Cretaceous shales and flysch-type sediments are several kilometres thick and crop out in extended areas.

It is the ungrateful task of this paper to attempt to demonstrate that there are still some hydrocarbon prospects in the Cretaceous flysch nappes of the Eastern Carpathians, despite the fact that today they are considered as being of little interest from an explorationists view.

STRATIGRAPHY AND STRUCTURE

Cretaceous sediments are involved in almost all of the East-Carpatnians nappes (Sandulescu et al., 1981a and 1981b, Sandulescu, 1984). In the Outer Dacids and Inner Moldavids they are mostly developed in flysch facies and are involved in a group of seven nappes, known in the Romanian geological literature as the Cretaceous Flysch Nappes. These are the more internal Black Flysch, Baraolt, Ceahlau and Bobu nappes of the Outer Dacids, and the more external Teleajen, Macla and Audia nappes of the Inner Moldavids (Fig. 1 and Encl. 1).

The **Black Flysch nappe** has a very complex internal structure and is characterized by four distinct imbrications. Each of them displays more or less distinct sequences which accumulated on a common basal mafic complex consisting of intraplate-type basalts, tholeiitic and calc-alkaline rocks (Sandulescu et al., 1981b). In the three external imbrications, flysch-type series were deposited during both Tithonian-Neocomian and Barremian-Aptian times. The slaty shales of the Tithonian-Neocomian flysch are very rich in graphite.

As all imbrications were affected by high-pressure/low-temperature metamorphic processes (Sandulescu et al., 1981b), the hydrocarbon potential of the Black Flysch nappe must be considered as negligible.

The **Baraolt nappe** is mostly made up of Early Cretaceous sandy-calcareous flysch which does not contain well developed source-rocks. Moreover, reservoirs involved in this nappe take in a very high structural position and, consequently, are deeply eroded. For these two reasons, the Baraolt nappe is also considered as non-prospective.

Despite the lacking prospectivity of the Black Flysch and Baraolt nappes, these two tectonic units have been mentioned here only because they form part of the Cretaceous Flysch Nappe system; they will not be further discussed in this paper.

The **Ceahlau nappe** is characterized by a very complicated internal structure, involving large imbrications. In the entire nappe, Tithonian-Neocomian sandy-calcareous flysch is well developed and is conformably overlain by a Barremian-Aptian sandy-shaly or shaly-sandy flysch sequence. In the internal parts of this nappe, Barremian-Aptian flysch is unconformably overlain by a thick pile of Albian conglomerates which, in turn, are unconformably covered by a hemipelagic to pelagic late Vraconian-Turonian sequence. Locally the latter rests directly on Aptian flysch. In contrast, in the more external imbrications of the Ceahlau Nappe, the Barremian-Aptian flysch grades upwards into a thick Albian sandy-shaly or sandy flysch sequence.

The **Bobu nappe** has a relatively simple internal structure which is characterized by large folds, involving Aptian-Turonian deposits developed in different facies. Aptian-early Albian strata are developed in a shaly-sandy flysch facies; middle Albian series consist of massive sandy flysch, locally containing conglomerate lenses. The lower parts of the late Albian (early Vraconian) are represented by shaly flysch which grades upwards into hemipelagic to pelagic series of the uppermost Albian (late Vraconian) and early Senonian.

The **Teleajen nappe**, which involves Hauterivian to Turonian series, has also a relatively simple internal structure, characterized by large, partly faulted, vertical or recumbent folds. Its sedimentary sequence begins with Hauterivian black-shales; these are overlain by Barremian-Aptian shaly-sandy flysch, containing black-shale intercalations. This flysch grades upwards into an up to 3 km thick sequence of Albian-Turonian shaly-sandy flysch, containing thick intercalations of massive sandy flysch.

The **Macla nappe** is characterized by a highly imbricated structure, involving only parts of its entire Albian-Turonian sequence. This unit consists of shaly flysch, containing red to purplish and black shale intercalations. Locally, in the highest part of this sequence, a thin level of sandy flysch is recognized.

The Ceahlau, Bobu, Teleajen and Macla nappes are overlain by a common late Senonian-early Miocene post-tectonic cover, attaining thicknesses of up to 1300 m.

The **Audia nappe** is characterized by a complex internal structure which is controlled by the lithological composition of the involved sedimentary sequences. Tightly imbricated structures occur in areas where mostly shaly Hauterivian-Aptian and Cenomanian-Turonian deposits dominate. In contrast, in areas where the upper part of the Audia Nappe sequence, consisting of Senonian to Eocene massive sandy flysch, crops out, the structural style is dominated by large synclines, separated by narrow, faulted anticlines.

The present overthrusted relationship between the above mentioned nappes was established during the following successive stages of the Carpathian orogeny:

(1) During Mid-Cretaceous times the Black Flysch and Baraolt nappes were emplaced; at the same time the internal parts of the Ceahlau nappe were folded and subsequently its leading edge covered by Albian-Turonian post-thrusting series.
(2) During intra-Senonian times the Ceahlau, Bobu, Teleajen and Macla nappes developed
(3) During the early Miocene (intra-Burdigalian), the latter were thrusted over Audia nappe and together with it over the Paleogene flysch zone.

SOURCE ROCKS

Fig. 2 summarizes the distribution of source- and reservoir-rocks in the Ceahlau, Bobu, Teleajen, Macla and Audia nappes. Although all five nappes contain source-rock intercalations, these occur at different stratigraphic levels. The oldest source-rocks accumulated during the Tithonian-Neocomian whilst the youngest were deposited during the Turonian. The longest period of source-rock accumulation spans the Tithonian-Aptian interval whereas the shortest one occurred during the middle Turonian.

In the **Ceahlau nappe**, the entire Tithonian-Neocomian interval contains around 2% TOC (for lithological details see Stefanescu and Micu, 1987); the kerogene is of Type I-II and is over-mature, as indicated by a R_0 greater than 2. The thickness of Tithonian-Neocomian source-rock shales varies between 350 m in the internal parts of the Ceahlau nappe and 500-600 m in its external parts. The Aptian and Albian flysch has a TOC of 1.1%; the kerogene is only of Type II and is also over-mature. Potential source-rock intercalations in the Aptian-Albian sequence have cumulative thicknesses ranging between 250 and 600 m.

Analysis on outcrop and well samples from the shaly-sandy Albian-Cenomanian flysch of the **Teleajen nappe** showed a TOC content varying between 0.8 and 1.35% and a kerogene of sapropelic type. R_0 values indicate that this flysch is at present located in the upper part of the oil window. The effectiveness of the Albian-Cenomanian flysch source-rocks is proven by the occurrence of oil and condensate seeps within the Teleajen nappe. The cumulative thickness of source-rock intercalations is of the order of 550 to 700 m.

The black Early Cretaceous series of the **Audia nappe**, which are associated with a few seeps, were more systematically analyzed (Baltes

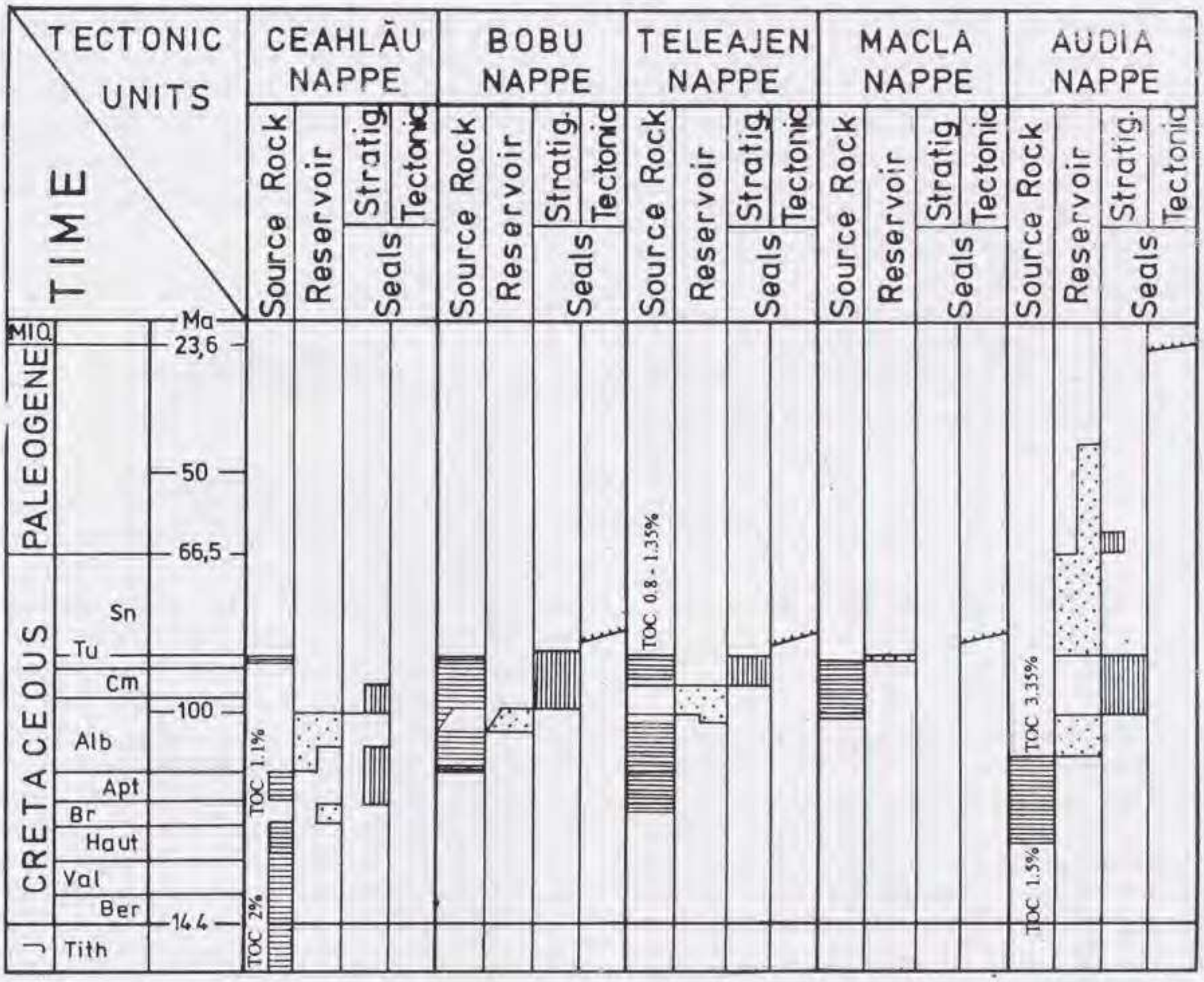

FIG. 2. Stratigraphic distribution of source- and reservoir-rocks in the Cretaceous Flysch Nappes.

et al., 1984) than the other Cretaceous formations of the Eastern Carpathians. Outcrop and core samples indicate a TOC range of 1.05-3.35%. Optical studies of the kerogen identified at least five main types of structured and one type of amorphous-colloidal organic matter. As a result of different and successive thermal flows, and also as a consequence of local burial histories and present tectonic positions, the organic matter shows extremely variable values of organic metamorphism ranging between R_o 0.55 and 2.02.

The Neocomian-Barremian black-shales, which contain siderite lenses, have an average TOC content of less than 1.5% and therefore a very weak petroleum generation potential. In contrast, Aptian-lowermost Albian shales, which attain a thickness of up to 200 m, yield TOC values reaching up to 3.35% and therefore have a much higher hydrocarbon generation potential; in places this sequence is still located near the top of the oil window whereas elsewhere it has passed through it an entered the gas generation window ($R_{o\ max}$ 1.9%).

It should be kept in mind, that the TOC values quoted above represent the residual potential of the respective source-rocks, the original organic content of which was presumably considerably larger.

Apart from the above discussed and identified source-rocks, the East-Carpathian Cretaceous flysch contains several additional potential source-rocks, the lithology of which compares favourably with proved source-rock intervals. For instance, the Albian flysch of the Bobu nappe is developed in a similar facies as the Albian flysch of the Teleajen nappe; the pelitic background of the Aptian flysch of the Teleajen nappe is similar to that of the Aptian flysch of the Audia nappe; the Cenomanian-Turonian shaly flysch of the Macla nappe can be compared with the Aptian black-shales of the Audia nappe. In this respect, is is noteworthy that wells drilled in the Macla nappe encountered important gas shows.

In conclusion, results of geochemical analyses and/or the occurrence of seeps indicate that, with the possible exception of the Bobu nappe, all of the above discussed Cretaceous flysch nappes contain effective source-rocks.

POTENTIAL RESERVOIRS

As shown in Fig. 2, all nappes under discussion contain reservoirs; however, their facies and stratigraphic position is different in each nappe.

The oldest potential reservoir section occurs in the **Ceahlau nappe** and consist of strongly tectonized, thick and massively bedded Barremian.flysch sandstones. The same nappe contains over 1500 m of Albian polymict conglomerates and sandstones, presenting a second objective section.

In the **Bobu nappe** the potential reservoir section is again Albian in age, but is developed in a thick bedded, sandy flysch facies which, macroscopically, shows good porosities. This section attains thicknesses of up to 1000 m and tends to wedge out towards western margin of this nappe where it is developed in a shaly flysch facies.

In the **Teleajen nappe** the potential reservoir section is of Late Albian-Cenomanian age; it is developed in a thick bedded, sandy flysch facies which in places attains thicknesses of the order of 1000 m and displays apparently good porosities (Fig. 3).

The **Macla nappe** is almost devoid of potential reservoir rocks. Only in places a Turonian feldspathic, thick bedded sandstone occurs, which never is thicker than 50 m.

The **Audia nappe** contains two potential reservoir sections. The older one is Albian in age and consists of 50-200 m thick, siliceous, hard, very low porosity sandstones. The younger section is Senonian-Eocene in age and and consists of 800-1000 m thick, massive sandy flysch that is characterized by good porosities.

SEALS AND TRAPS

Most of the above discussed potential reservoir sections are encased in thick shales, partly developed in source-rock facies; these provide viable top and seat seals (Fig. 2). Shale intercalations in the reservoir sections can provide for local intra-formational seals. Only the Turonian sand in the top part of the Macla nappe and the Senonian-Eocene sands of the Audia nappe apparently lacked an initial normal stratigraphic seal. However, both the Macla and Audia nappes are now tectonically sealed by shales contained in the basal parts of overriding nappes. Thrust faults can also provide potential seals for subjacent tectonic units. This does, however, not apply for areas where Albian conglomerates form the base of the Ceahlau nappe. Surface and subsurface geological data indicate that horizontal displacement on the individual Cretaceous flysch nappes is on average in excess of 10 km.

Lateral shale-out of potential reservoir sections may provide for stratigraphic (lithologic) traps. Such a shale-out is indicated, for instance, for the Albian-Cenomanian sandstones of the Teleajen nappe. Similar lateral facies changes may also occur in the other nappes.

In terms of potential structural traps, it must be kept in mind that the internal structuration of each nappe differs. The Ceahlau, Macla and Audia nappes, particularly in areas where only shaly deposits outcrop, display a very complex, generally tightly imbricated structure which is not favourable for the development of structural traps and the preservation of hydrocarbon accumulation. In contrast, the internal structure of the Bobu and Teleajen nappes, and in those parts of the Audia nappe

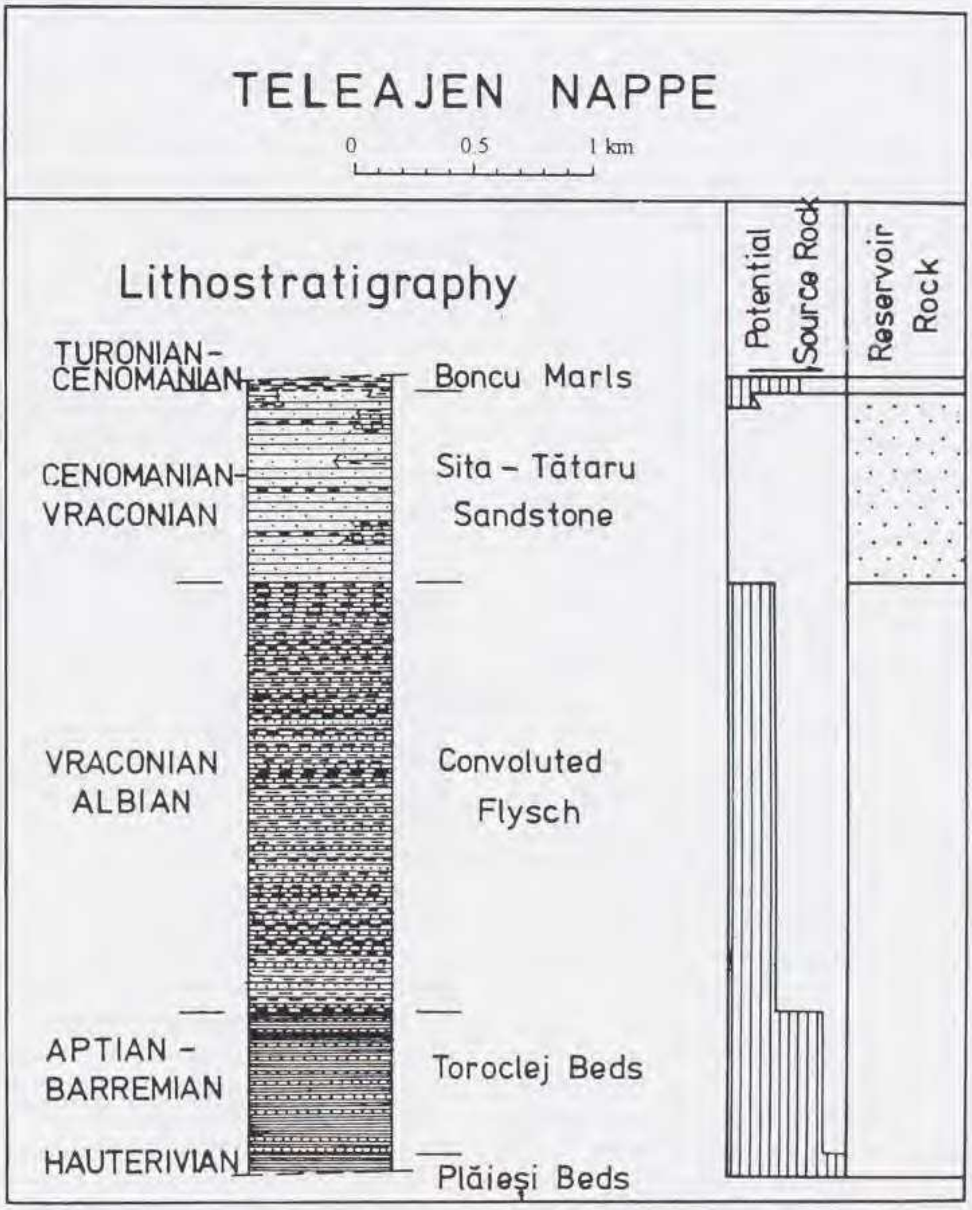

FIG. 3. Lithostratigraphy of the Teleajen nappe

where thick Senonian-Eocene sandstones are present, is characterized by large synclines and anticlines which are partly affected by steeply dipping thrust faults (Fig. 6). In such faulted structures, most of the reservoir sections occur in a high structural position and are consequently deeply eroded. Therefore, potential structural traps are restricted to features which are sealed by overriding nappes.

HYDROCARBON PROSPECTS

Taking the above into account, conditions for generation, accumulation and preservation of hydrocarbons is probably most favourable in the Teleajen nappe. Therefore, the following discussion will focus on this tectonic unit.

The stratigraphic sequence involved in the Teleajen nappe consists, in ascending order, of the following members (Fig. 3): locally the sequence begins with 50 m of Hauterivian black clays and siltstones. These grade upward into up to 500 m thick Barremian-Aptian shaly-sandy flysch which has the same black-shale pelitic background as the Hauterivian. The next following unit consists of 2500 m of Albian shaly-sandy and sandy-shaly flysch, containing thin black-shale intercalations. This member is capped by 750 m of late Albian-early Cenomanian massive sandy flysch, locally containing lenses of polymict conglomerates. The topmost member consists of 20-400 m of late Cenomanian-Turonian shaly-sandy flysch. Older than Hauterivian deposits are not known from the Teleajen Nappe which, like all the tectonic units of the Cretaceous Flysch nappes, is completely detached of its initial basement. The Hauterivian-Albian and late Cenomanian-Turonian series contain effective source-rocks whereas the Late Albian-Early Cenomanian sands have excellent reservoir characteristics (Fig. 4).

During the Coniacian the area of the future Teleajen nappe was overridden by the Ceahlau and Bobu nappe and prior to the Santonian, the Teleajen nappe was thrusted over the next external unit, the area of the Macla nappe, which, in turn, was also deformed. At the same time the entire sedimentary sequence making up the Teleajen nappe was folded for the first time. During the late Senonian to Oligocene, an over 1000 m thick sequence of neo-autochthonous sediments was deposited on the Teleajen and the other Cretaceous Flysch nappes. During this time, the area of the Audia nappe had not yet been deformed and formed part of the Carpathian foreland basin. During the early Miocene, the Ceahlau, Bobu, Teleajen and Macla nappes were thrusted over the Audia nappe and, together with it, over the Paleogene flysch zone. During this late phase of the Carpathian orogeny the Teleajen nappe was deformed a second time.

Fig. 5 summarizes the burial and maturation history of the Teleajen nappe. In parts of the future Teleajen nappe, Hauterivian-Early Aptian series had already entered the oil window during the Coniacian, that is prior to its involvement into the Carpathian orogen (Fig. 5a). However, hydrocarbons generated and expelled from these source-rocks accumulated either in stratigraphic traps in Late Albian-Early Cenomanian reservoirs or were lost as at that time structural traps had not yet been formed.

At the end of the Coniacian, subsidence of the Teleajen basin ceased and, prior to the late Campanian, the Ceahlau and Bobu nappes were thrusted over the Teleajen nappe, which in its turn was thrusted over the Macla Nappe. At the same time the internal parts of the Teleajen Cretaceous flysch basin were strongly deformed, resulting in the development of structural traps.

During Campanian to end-Oligocene times, the Teleajen nappe subsided under the load of its neo-autochthonous sedimentary cover. During this time, the Late Aptian-Turonian source-rocks entered and partly passed through the oil window (Fig. 5b). Hydrocarbons generated presumably accumulated in earlier formed structural traps. During the early Miocene phase of the Carpathian orogeny, the configuration of these traps was modified, causing loss of hydrocarbons. However, Albian-Turonian rocks, including reservoir- and source-rocks, remained till the present in the oil window. This is in keeping with the occurrence of light oil seeps in the Teleajen nappe, immediately in front of the Bobu nappe.

The late Albian-Cenomanian reservoirs of the Teleajen Nappe are involved in imbricated, folded structures. In areas where this nappe outcrops, these structures are deeply eroded and their original stratigraphic seals have been removed (Fig. 6). Therefore, the outcropping parts of this nappe must be considered as essentially non-prospective. However, further to the West, where the Teleajen nappe is covered by the Bobu nappe, subthrust structures may still be effectively sealed, either by Cenomanian-Turonian marls or by the sole-thrust of the Bobu nappe. Structuration of the Teleajen nappe beneath the Bobu nappe is presumably characterized by a similar style as in its outcropping parts. Consequently, if beneath the Bobu nappe appropriate structures, involving thick Late Albian-Cenomanian reservoirs, can be identified, these may present viable exploration targets. However, in view of the complexity of the structuration of the Teleajen nappe, it remains to be seen whether such targets can be defined by the reflection-seismic tool.

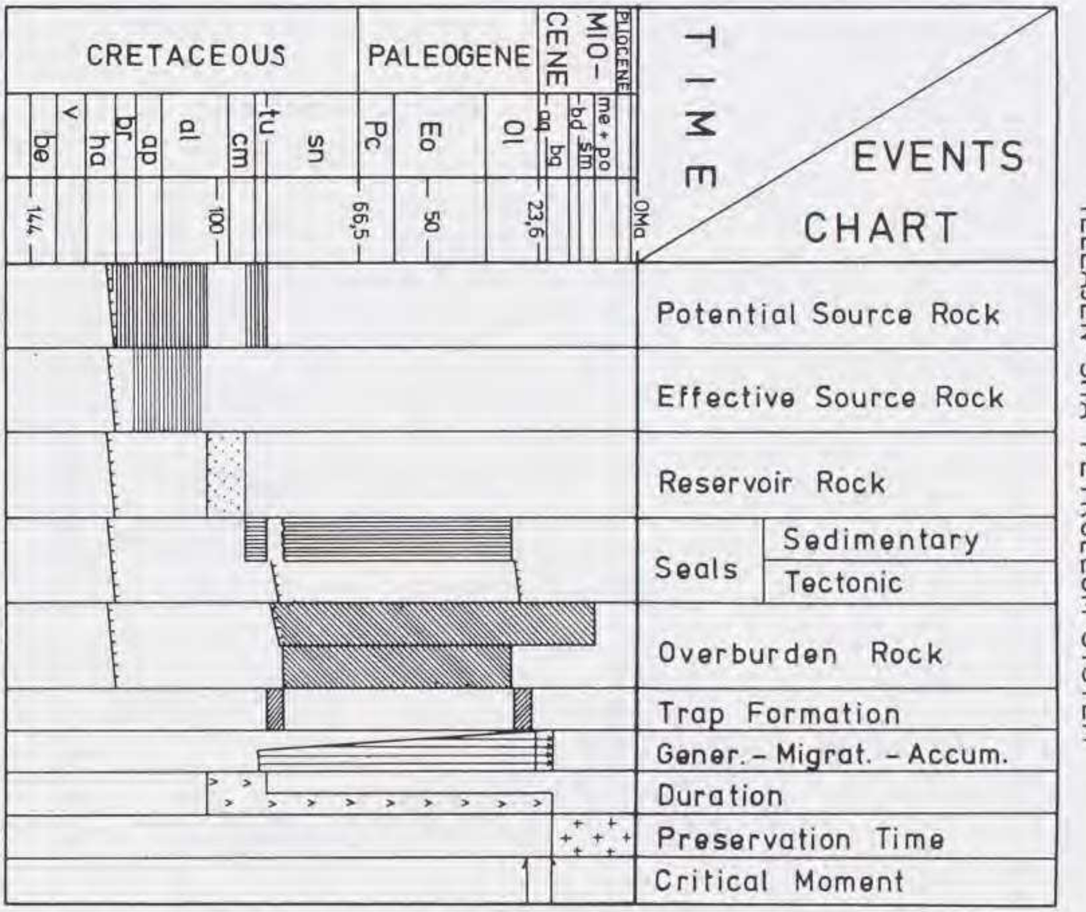

FIG. 4. Teleajen nappe petroleum system

CONCLUSIONS

The Cretaceous flysch of the Eastern Carpathians contains several well developed reservoir- and source-rock intervals. Geochemical analyses and the occurrence of seeps show that source-rocks have variably entered the oil and even the gas window.

During the evolution of the Cretaceous flysch basin towards a petroleum system, early generated hydrocarbons accumulated either in stratigraphic traps or were lost due to unfavorable timing between peak generation and the formation of structural traps. Hydrocarbons accumulated in stratigraphic traps, were presumably destroyed during the orogenic phases.

Part of the source rocks are at present still located within the oil window. Hydrocarbons generated during the syn-deformational stages of the Carpathians were presumably structurally trapped. Polyphase deformations and late uplift and erosion of the Carpathians resulted in destruction of such accumulations, mainly by removal of their stratigraphic seals. However, in sub-thrust positions, such accumulations, which are either stratigraphically or tectonically sealed, may still be preserved, for instance in the area where the Teleajen nappe is covered by the Bobu nappe, or the latter is covered by the Ceahlau nappe.

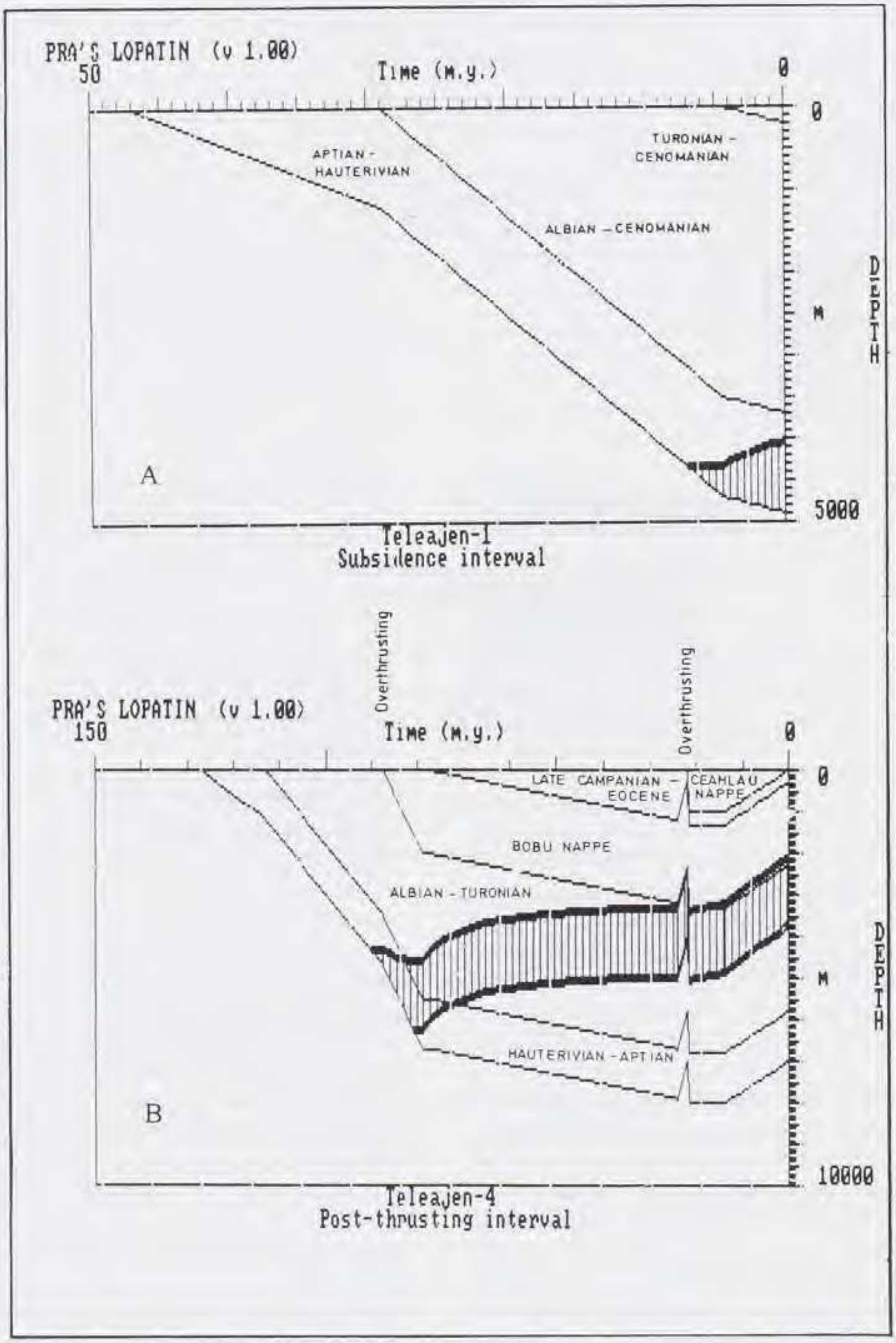

FIG. 5. Teleajen nappe burial and maturation history. Vertically hachured area corresponds to oil window.

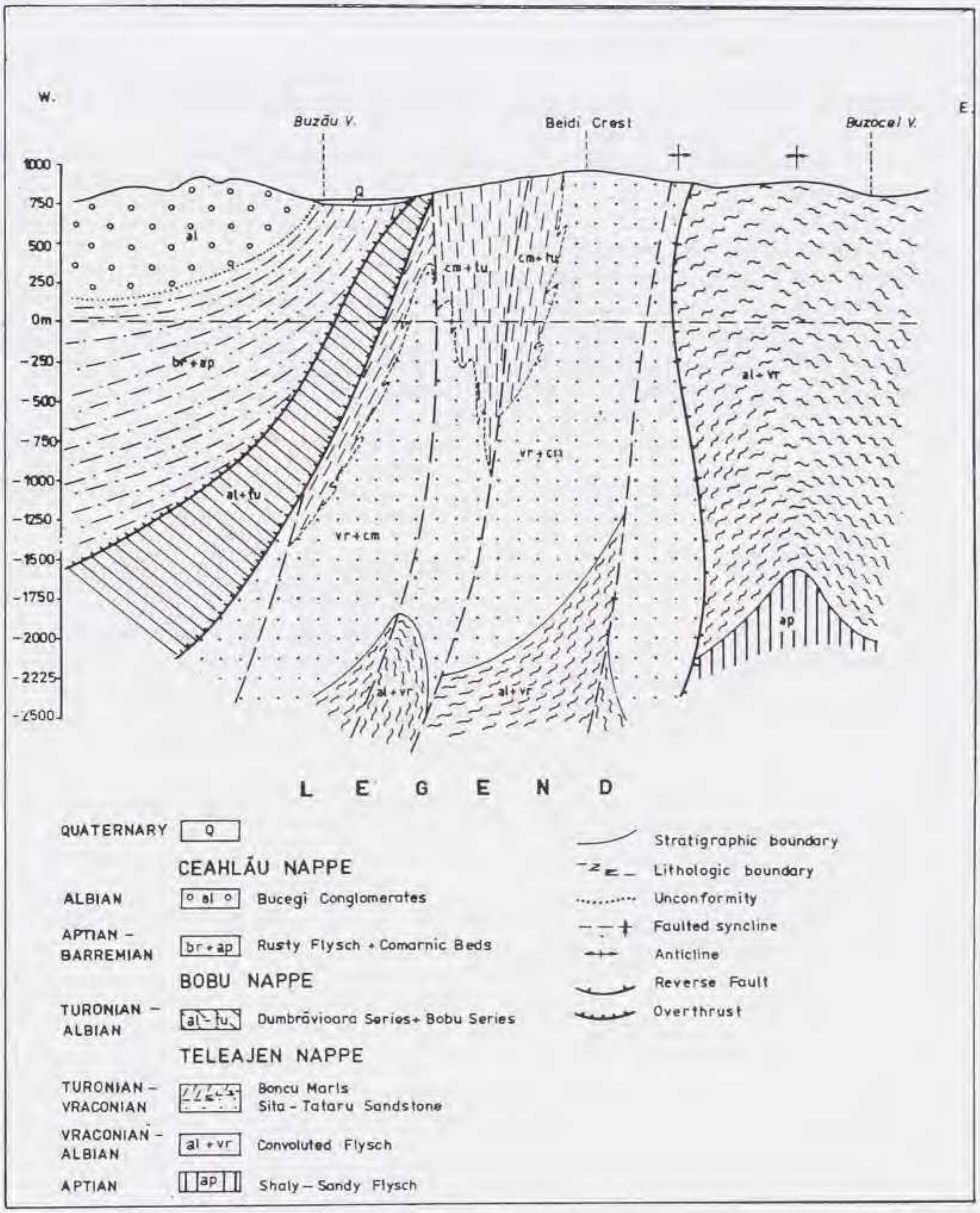

FIG. 6. Geological cross-section at the boundary between the Bobu/Teleajen nappes

The prospectivity of the East-Carpathian Cretaceous flysch nappes cannot be ruled out, particularly in terms of subthrust prospects sealed by the sole-thrusts of higher nappes. The main risk of such a play is the reflection-seismic definition of drillable structures. Hydrocarbon charge and reservoir risks play a secondary role.

We conclude, that albeit speculative hydrocarbon prospects still exist in the East-Carpathian flysch nappes of Romanian.

Acknowledgements- The authors express their thanks to Dr. Serban Veliciu for his help in generating the burial diagrams. The constructive and critical remarks by Dr. P.A. Ziegler and Dr. F. Roure on an earlier version of this manuscript and Dr. Ziegler's editorial efforts are gratefully acknowledged.

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Enclosure

Encl. 1 Persani-Ciucas-Pietroasa simplified geological cross-section. For location see Fig. 1.

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